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INTERFERENCE MEASUREMENTS OF WAVE LENGTHS IN THE IRON SPECTRUM (2851–3701)

By Keivin Burns

With Notes on Comparisons of Lengths of Light Waves by Interference Methods, and Some Wave Lengths in the Spectrum of Neon Gas

By W. F. Meggers

CONTENTS

INTRODUCTION

The determination of accurate wave lengths in the spectra of iron and of other elements has recently been undertaken at the Bureau of Standards. The need for wave-length determinations

of great accuracy has long been felt by physicists, chemists, and astronomers. As an example, it is impossible to make a complete spectral analysis of iron, owing to our lack of exact knowledge of the spectra of some elements of the ferrous group. Before any reliable wave lengths can be obtained there must necessarily be a consistent fundamental system. On account of the irregularities existing in the Rowland system of wave lengths, an international conference of eminent spectroscopists in 1907 recommended the adoption of a new system of wave lengths based on the length of the red cadmium line as determined by Benoit, Fabry, and Perot by direct comparison with the meter. In this system, by means of the interferometer, secondary standards were to be determined, each by three independent observers, in the iron spectrum at intervals of 50 Å (0.005 μ); that is, the wave length of each standard was to differ by 50 Å from the wave lengths of its nearest neighbors to the violet and red. All wave lengths are to be reduced to 760 mm and 15°. Wave lengths measured on this system are designated by I. Å. (international Ångström). This same group of spectroscopists recommended in 1913 that the standards be observed, not at intervals of 50 Å, but of 10 Å, thus greatly increasing the work of determining a fundamental system. The Bureau of Standards has undertaken to do the part of this work for which the present need seems to be the greatest, and this paper presents the first installment of wave lengths to be measured here in keeping with the international plan. As soon as a satisfactory system of standards has been obtained we can proceed to the accurate measurement of wave lengths in the spectra of all the elements.

The spectrograms upon which this work is based were obtained at Marseille, in the laboratories of Messrs. Buisson and Fabry. The interferometer plates which were used there were afterwards very kindly loaned to the Bureau of Standards, and the phase change was redetermined here by W. F. Meggers. His results are found in the article which follows directly after this paper. All of the measuring and the greater part of the computing upon which the wave lengths in the iron spectrum are based was done by Mr. Meggers.

It is a pleasure to acknowledge indebtedness to Messrs. Buisson and Fabry for their interest and help; and to Director Campbell, who, by appointing me Martin Kellog Fellow of the Lick Observatory, University of California, made it possible to take the plates necessary for this investigation.

PURPOSE

At the time this investigation was undertaken (May, 1913) no international standards of wave length had been decided upon in the region to the violet of 3700 Å, and one object was to make measurements which might be combined with the results of other observers to furnish international standards. While this work was in progress international standards [1] were published for the region to the red of 3370 Å; but as yet only one series [2] of interferometer measurements of wave lengths shorter than 3370 Å has been published. Another object which was kept in view in undertaking this work was the determination of standards at intervals of 10 Å. Since this was recommended afterward by the wave-length committee of the Solar Union,[1] its importance will not be insisted upon here.

APPARATUS

It was necessary to use rather high dispersion and resolution in the spectograph in order to obtain a sufficiently large number of isolated lines. The apparatus was essentially the same as that used by former observers for the purpose of measuring secondary standards of wave lengths. The light of the iron arc was focused upon the etalon by the simple quartz lens, L_1, Fig. 1. The etalon, made of invar, was 3.75 mm thick. The interference plates were quartz disks, whose inner surfaces were coated with a film of nickel, cathodically deposited. These plates were just as they had been used by M. M. Buisson and Fabry some seven years before, a fact that is of interest in the discussion of the phase change.

[1] Kayser et alii, Astroph. J., 39, p. 93; 1914.
[2] Buisson and Fabry, Astroph. J., 28, p. 169; 1908.

The reflecting power of the films is satisfactory throughout the region under discussion. The rings are projected upon the slit by the quartz-fluorite lens, L_2. In the present instance the slit is mounted as indicated in Fig. 1, otherwise the spectograph is as described by Buisson and Fabry.[3] The light from the arc after passing through the slit falls upon the concave mirror M, which sends a parallel beam of light to the grating G. The slit and grating are so close together, as seen from the mirror, that the aberration due to the mirror is small, and in any case the effect is very small along the diameter of the ring system which is measured. The grating was ruled by Rowland. It has a radius of 635 cm and it is ruled about 580 lines per millimeter, having some 80 000 lines in all. The grating was used exclusively in the first

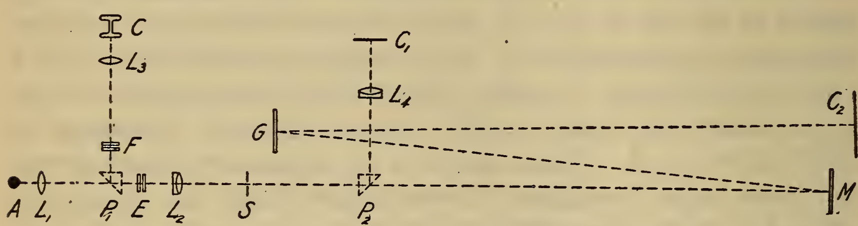

FIG. 1.—*Plan of apparatus*

order. In the present mounting the dispersion in this order is about 5 Å per millimeter. Using a slit 0.04 mm wide, lines 0.2 Å apart are easily measurable. The spectrum is focused by the grating upon the photographic plate at C_2. A flat plate was used, which gave practically perfect definition from 2900 Å to 3500 Å. Measurements extending to 3700 Å show that the slight falling off in definition had no appreciable effect upon the resulting wave lengths.

Two holes cut in a brass plate served as a guage to show the ratio of the size of the ring system on the slit to the diameter of each ring on the photographic plate. This plate was slid into position along a groove in the front of the slit head. The cadmium light is focused upon the etalon by the simple quartz lens, L_3. The filter F cuts off all the light excepting that from the red line. When this cadmium line is to be photographed, the totally reflecting prisms P_1 and P_2 are put into position, as shown in the figure.

[3] Fabry and Buisson, Jour. de Phys., 9, p. 229; 1910.

P_1 throws the light upon the etalon and the rings are focused upon the slit by the quartz-fluorite lens, L_2. After passing through the slit the cadmium light is reflected by the prism P_2 into the objective of a small camera, L_4. The rings are photographed at C_1 without having passed through any dispersive element. In both of the cameras, C_1 and C_2, it is possible to slide the plate holder up and down, which provides for the making of several exposures on the same plate.

SOURCES

The standard wave length was furnished by a Michelson H tube, which was kept at a temperature of about 315°. It was necessary to bathe plates in order to photograph rings from this rather faint source in a reasonably short exposure. Fast plates, Lumière sigma or Seed 27, were bathed with dicyanin and ammonia. The iron arc was fed by the city current at 220 volts, and the arc burned between round electrodes 8 mm in diameter. In Table 1 are found some further data relating to the conditions of the arc and the length of the exposures. The amperage is seen to vary from 3.3 to 4, the mean being 3.6. While the length of the arc varies from 1.5 to 5 mm, only 5 out of 25 exposures were made with the arc shorter than 4 mm. The arc was stationary with the positive above, excepting on 6 exposures. In the case of 4a and 7c the arc was raised and lowered continuously, so that light from the positive pole might fall in turn upon all parts of the ring system.

On plate 8 the poles were interchanged by means of a switch several times during each exposure. It may be said that the polarity appears to have no effect upon the wave length. Excepting for the two lines, 3497.8 Å and 3610 A, the length of the arc within the limits used seems to be without effect. In the case of these two lines there may be a displacement, amounting to less than 0.005 Å, due to change in the length of the arc, but the reality of this displacement is quite uncertain. It is well known that many ultra-violet lines are broad when heavy current is used, and undoubtedly some of these lines would be shifted by increasing the current. But the lines are very sharp for the most part

under the conditions used in making these plates, and no shift is to be expected from the use of a current less than 4 amperes.

In Table 1 the column headed "Temperature" contains the mean temperature at the etalon. Under "Arc" is given the length of the arc; under "Cadmium" the number of measurable exposures on the cadmium line in connection with each plate. Other column headings are self-explanatory.

TABLE 1

Plate	Exposure	Temperature	Bar	Amperes	Arc	Time of exposure	Cadmium	Slit
		°C	mm		mm	min.		mm
1	a	16.4	760	3.5	5.0	1	....	0.04
	b	16.4	760	3.5	5.0	2	....	.04
2	a	16.6	758	3.5	5.0	½	2	.04
	b	16.6	758	3.5	5.0	1	2	.04
	c	16.6	758	3.5	5.0	2	2	.04
	d	16.6	758	3.5	5.0	4	2	.04
3	a	17.2	759	3.3	4.5	8	4	.08
	b	17.2	759	3.3	4.5	4	4	.08
	c	17.2	759	3.3	4.5	2	4	.08
	d	17.2	759	3.3	4.5	1	4	.08
4	a [4]	17.2	759	3.3	2.0	5	4	.08
	b	17.2	759	3.3	4.0	30	4	.08
6	....	17.8	758	3.5	5.0	20	4	.12
7	a	17.6	756	3.5	5.0	10	4	.12
	b	17.6	756	4.0	1.5	11	4	.12
	c [4]	17.6	756	4.0	1.5	5	4	.12
	d	17.6	756	3.7	5.0	6	4	.12
	e	17.6	756	3.7	5.0	1	4	.12
8	a [5]	17.6	761	3.9	4.0	5	3	.12
	b [5]	17.6	761	3.9	4.0	10	3	.12
	c [5]	17.6	761	3.9	4.0	1	3	.12
	d [5]	17.6	761	3.9	4.0	⅓	3	.12
9	a [6]	18.0	761	3.4	2.0	10	....	.12
	b [7]	18.0	761	3.4	2.0	10	....	.12
10	a [8]	18.4	761	3.9	4.0	60	....	.12

[4] Displaced continuously.
[5] Poles interchanged at intervals.
[6] Positive above.
[7] Positive below.
[8] Poor.

METHOD

The method used is fully discussed by Buisson and Fabry.[9] The formulas are given below, but it seems unnecessary to repeat their derivation.

[9] See Note 2, p. 181.

ORDER

p = order of the center of the ring system.

P = order of a given ring (whole number).

θ = angular distance between the reference marks as seen from the Gauss point of the ring projection lens.

r = the distance between these marks on the plate.

d = the diameter of a ring.

$$p = P + P\, d^2 \frac{\theta^2}{8\, r^2}$$

$$\lambda_1 = \lambda_2 \frac{p_2}{p_1}$$

REDUCTION TO NORMAL CONDITIONS

Let γ be the correction in wave length necessary to reduce the observed value to what it would be under normal conditions.

λ_o = wave length under normal conditions.

η_o = refractive index of air corresponding to λ_o.

η'_o = refractive index of air corresponding to λ 6438 under normal conditions.

M = density of the air under the conditions of observation.

M_o = = density of the air under normal conditions. Then

$$\gamma = \lambda_o\, (\eta_o - \eta'_o)\, \frac{M - M_o}{M_o}$$

CORRECTION FOR PHASE CHANGE

(*a*) WEDGE-SHAPED INTERFEROMETER.—Let η be the correction for phase change, expressed in wave length.

Let λ and λ' be the wave lengths, respectively, of the line in question and of the standard (cadmium red); q and q' the corresponding orders at a point in the interferometer marked by a cross; and e and e' the corresponding thickness. Then $2\,(e - e')$ =

$$\epsilon = q\, \lambda - q'\, \lambda', \text{ and } \eta = \frac{\epsilon\lambda}{2e}$$

(*b*) ETALONS OF DIFFERENT THICKNESS.—Let T_1 be the thickness of one etalon; T_2 the thickness of another; and T that of the etalon in connection with which the phase change is required.

Let λ_1, λ_2, and λ be the corresponding wave lengths obtained by means of these etalons without correction for phase. Then

$$\eta = \frac{T_1(\lambda_2 - \lambda_1)}{T_2 - T_1} \times \frac{T_2}{T}$$

Messrs. Buisson and Fabry measured the phase change by means of a wedge-shaped interferometer. Mr. Meggers used etalons of different thicknesses. In this case the wave lengths of the neon lines were observed by means of an etalon of 2 mm thickness and by one of 15 mm thickness. The correction due to phase change as determined by Messrs. Buisson and Fabry and seven years later by Mr. Meggers differs by about 0.003 Å (3.75 mm etalon) for the interval 6400 Å to 3400 Å. (The former determination was made over five years before my work was done, and the latter determination followed my work by a year and a half.) This difference may be real; however, we have treated it as partly accidental and we have used the weighted mean of the two determinations. Since Mr. Meggers's result was obtained closer in time to the observations of wave length, his value was given double the weight of the other. The values at 3400 Å are: B & F + 0.0084 Å; M., +0.0117 Å.

The correction for dispersion of the atmosphere amounted to only 0.0005 Å at most. The mean reduction for the six plates was added to the correction for phase change and applied to the mean wave length of each line.

REDUCTION

The cadmium line was measurable in connection with six plates (20 exposures). If every line had been measured an equal number of times on each plate, the mean of all measurements could be taken directly; but each plate differed systematically from the mean (due largely to accidental errors in measurement of the cadmium line), and some lines were measured almost entirely on plates that were above the mean. Other lines were measured mainly on plates which were below the mean. To correct these lines for this systematic difference, which might amount to 0.005 Å in an extreme case, there was formed what shall be called the fundamental mean. The mean of all exposures on a plate was

taken as the value for each line on that plate, and the mean of the values thus obtained was formed for all lines occurring on four or more plates. In this way the cadmium line in connection with each plate affects the mean in about the same degree, regardless of the number of exposures on the plate.

Forty-eight lines distributed through the whole region were found on four or more plates, and many of them on all six plates. Differences between this series of means and the observed value were now plotted for each exposure and corrections were made by means of a straight line, which represented the observations. This line was inclined slightly in some instances with respect to the axis of wave length. The largest correction was 0.006 Å. From these corrections the probable value of a systematic error was found to be ±0.0011 Å. In other words, if we were interested in determining the wave length of the red cadmium line, using these iron lines as standards, the probable error of the determination would be just over ±0.002 Å. This is fairly satisfactory, considering the interval between these lines and the red cadmium line and the small thickness of etalon that had to be used.

TABLE 2

Mean Wave Lengths from Individual Plates

Plate \ λ	3370.776		3380.104		3383.978	
	Obsd.	Corr.	Obsd.	Corr.	Obsd.	Corr.
2	776	776			974	975
3	774	776	102	104		
4	770	776	100	106	973	979
6	780	777	107	104		
7	779	776	108	105	981	979
8	779	776	106	102		
Mean	0.7763	0.7762	0.1046	0.1042	0.9760	0.9777
Mean by exposures		.7761		.1041		.9777

In Table 2 are given the individual values of the wave lengths of three lines chosen arbitrarily in the middle of the series. The first column under the wave length gives the measured value, the

second column gives the value corrected for the systematic difference of the plate from the mean. It is readily seen that when a line has been measured on several plates it is immaterial whether the mean of the corrected or uncorrected values be taken. If the line occurs on only three plates, the corrected mean may differ by a few thousandths of an Ångström from the uncorrected mean. In these means each plate was given equal weight, although one had four exposures. Giving each exposure equal weight the corrected mean is written at the bottom, and a comparison of this with the mean by plates shows that there is no appreciable difference between the two.

TABLE 3

Order at λ3370 as Determined from Separate Rings

Plate	Exposure	Order		2−1
		First ring	Second ring	
2	c	22321.125	123	−2
	d	124	127	+3
3	a	138	138	±0
	b	147	147	±0
	c	121	127	+6
4		127	149	+22
6		098	118	+20
7	a	114	123	+9
	b	120	132	+12
	c	109	132	+23
	d	136	138	+2
8	a	131	136	+5
	b	146	172	+26
	c	22321.146	143	−3
Mean				+9

In Table 3 are given the values of the order as determined from the first and second ring for each exposure on the line 3370. Only two rings were measured on each line. The tendency for the second ring to give a larger value of the order is common to all lines, but the reason for this could not be found. If one is right and the other wrong, the wave lengths are one part in four million in error for this reason alone.

SOURCES OF ERROR

The angle θ was measured in two different ways and the agreement of the results from the two measurements was not perfect. It is possible that the value of θ which was used may have caused a systematic error of 0.001 Å, but that is the extreme limit. It is probable that the error arising from this source is of no importance.

The measurements were examined for an effect of varying exposure. Interference rings are sharper on the outside than on the inside and it was feared that increasing exposure might tend to shift the center of gravity of the image toward the center of the system, resulting in increased wave length. No such effect was found, although very weak and very strong exposures of the same line were measured in several instances. This asymmetrical form of the interference rings may cause apparent shift towardt he red if the line is broadened. Such an effect is not apparent in the present work in case of lines marked "h" when these values are compared with grating measurements. The shifts due to instrumental causes in case of broad lines measured by interference are probably smaller than the displacements to which grating measurements of poor lines are liable, when the resolution and dispersion of the grating are varied.

PROCEDURE IN MAKING A PLATE

The usual procedure in making a plate is illustrated by the work on May 30, 1913. Plates are bathed in order to sensitize them to the red and put to dry. Fresh plates had to be bathed every day since the red sensitive plates do not keep very well unless held at a low temperature. While they are drying the gas is lighted under the cadmium lamp. By the time this is heated to the proper degree the grating, which is kept overnight in a drying chamber, has been put into place and a focus plate has been taken and developed. Also the parallelism of the interference plates has been adjusted and the etalon has been put into position and the center of the rings brought to the middle of the slit. For adjusting the parallelism of the plates I observed the rings due to the mercury lines; the light was furnished by a Cooper Hewitt lamp. The stained plates are now ready for use, and the cadmium is at the proper tem-

perature. After testing the position of the cadmium lamp the totally reflecting prisms are put into place and two exposures of three minutes each are made on the cadmium rings. The cadmium camera must now be closed and the spectrograph opened and the prisms removed. The arc is adjusted on the etalon and the spectrograph plate holder opened. A 30-minute and a 10-minute exposure is made on the iron. This plate holder must now be closed, the spectrograph opened, and the prisms put into place. The cadmium camera is opened and two exposures of 3 minutes each are made on the cadmium rings. The etalon is now removed and two exposures of 20 seconds made on the gauge, which has to be slid into place. This finishes the cadmium plate and the holder is closed and removed. The spectrograph must be opened again and the prisms removed. Then the spectrograph plate holder is opened and a 7-second exposure made on the gauge. This completes the observation.

The temperature of the etalon is read at the first and the third cadmium exposure. The temperature of the cadmium lamp is read at each exposure. On account of using two cameras in different parts of the room and of the necessity for opening the spectrograph, there are many accidents which happen to plates. However, flaws in the red sensitive plates caused the greater part of the actual loss of exposures. On account of the location of the Marseille laboratory in the center of the city between two of the busiest streets, and due to the somewhat temporary nature of the mounting, it was not possible to make long exposures with satisfactory results. All attempts to get the faint lines of wave length shorter than 3000 Å failed through displacement of the apparatus during the long exposures. Six satisfactory plates were secured, and three or four other plates have one or two measurable exposures of the iron, but through accident these lack exposures of cadmium rings or reference marks. These latter plates, and in fact all of the plates, might be reduced by means of the I. A. Standards, of which there are six that can be measured. The wave lengths would be about 0.001 Å greater if reduced by these standards.

RESULTS

In Table 4 the column headed "Notes" contains the intensity and in some cases a letter indicating the character of the line at 6 amperes. It is to be noted that these lines were not reversed when the current strength was 4 amperes. The letters have significance as follows: b = broad, d = double, h = hazy, l = shaded to red, r = narrow reversal, R = broad reversal, and V = shaded to violet.

The column headed "p. e." contains letters to indicate the dependence which may be put upon the given value. The best lines are indicated by A, those marked by B are fairly good, but C means that the line in question should be used with caution.

TABLE 4

Wave Lengths in the Iron Spectrum

(760 mm and 15°)

λ	Notes	p. e.	λ	Notes	p. e.	λ	Notes	p. e.
2851. 802	8	C	3116. 638	5	A	39. 440	8	B
2899. 422	4	C	25. 665	6	A	44. 189	8	B
2918. 031	5	C	29. 340	4	C	54. 367	4	A
41. 348	8	B	34. 115	—Ni[1]	A	57. 598	4	C
59. 998	4	C	51. 349	6b[2]	C	65. 622	6	A
87. 298	5	A	57. 043	4	B	71. 005	6b	A
90. 397	4	B	60. 660	6	B	80. 264	5	A
2999. 518	5r	B	75. 450	6	A	84. 593	4	C
3003. 036	4	B	78. 014	6	C	86. 760	8	A
11. 487	4	B	80. 229	8b	C	90. 992	4	B
17. 634	5r	B	84. 900	4	A	3298. 136	5	A
18. 989	5r	B	91. 664	5d	A	3305. 977	8	A
24. 038	5r	B	3199. 527	6b	C	06. 358	8	A
30. 156	4	A	3200. 478	6b	A	14. 746	6	A
40. 435	4	A	05. 401	7b	A	23. 741	4	A
45. 086	4	C	15. 944	5b	B	28. 870	4	A
55. 268	4	A	17. 385	4	A	37. 670	4	A
68. 180	4	A	22. 072	6b	A	47. 930	4	A
75. 726	5r	A	25. 792	8h	A	55. 232	4	A
83. 747	4r	A	30. 972	6b	B	69. 553	—Ni[1]	A
91. 582	4r	A	33. 056	5	A	70. 787	6	A
3098. 194	3	C	36. 227	6	A	80. 115	5	A

TABLE 4—Continued

Wave Lengths in the Iron Spectrum—Continued

λ	Notes	p. e.	λ	Notes	p. e.	λ	Notes	p. e.
83. 988	5	C	76. 707	5r[3]	A	3603. 207	5	A
92. 659	5	B	85. 343	6	A	06. 682	5	A
94. 588	4	A	95. 292	4V	A	10. 159	5h	B
96. 981	3	B	97. 111	4	B	12. 081	4	C
3399. 339	6	A	3497. 847	5r	B	17. 789	6	A
3401. 523	4	A	3506. 500	5	A	21. 462	6	B
02. 262	4	B	13. 822	5	A	22. 004	6	B
07. 464	71, d	A	21. 266	5r	B	23. 188	5	A
13. 136	7	A	27. 796	4	B	25. 150	6	B
15. 540	4	C	29. 819	4	B	38. 298	6	B
17. 844	6	A	36. 558	6	A	40. 392	6	B
18. 513	5	A	41. 089	6h	A	45. 826	4	C
24. 289	6	A	42. 080	6	A	51. 469	6	B
27. 122	6	B	45. 643	5	A	59. 520	5	B
28. 197	6	A	54. 928	8h	B	76. 312	4	B
43. 882	6R	C	56. 878	6h	A	77. 636	6[4]	B
45. 152	4	A	58. 519	5r	C	83. 057	4	C
47. 282	6	A	71. 999	7h	B	84. 112	5	C
50. 332	6	A	78. 689	—Cr[1]	A	89. 457	6	C
58. 306	3	B	89. 108	4	A	3595. 054	3	C
59. 916	4	A	93. 488	—Cr[1]	B	3701. 082	6	C
68. 850	4	B	3594. 632	5	A			

NOTES TO TABLE 4

1. Lines of impurities are not as yet recommended for standards. In case the impurity is present only in small quantities, it is probable that the wave length of the impurity lines will be constant. Until the matter has been thoroughly investigated I prefer to use no such line.

2. This line is included because it shortens the gap between 3129 Å and 3157 Å. The measurements are discordant.

3. A line of intensity 2 at 3476.86 Å.

4. This line has been measured by Buisson and Fabry, by Pfund, and by Eversheim.[10] It is not reliable on my plates on account of a close companion of too great intensity.

TABLE 5

Comparison with Other Interference Measurements

B & F	B	P	I Å	B−B & F	B−P	B−I. Å.
2851.800	802	....	....	+2	....	....
2941.347	348	....	....	+1	....	....
2987.293	298	....	....	+5	....	....
3030.152	156	153	....	+4	+3	....
3075.725	726	726	....	+1	±0	....
3125.661	665	661	....	+4	+4	....
3175.447	450	....	....	+3	....	....
3225.790	792	....	....	+2	....	....
3233	056	055	....	....	+1	....
3271.003	005	008	....	+2	−3	....
3323.739	741	738	....	+2	+3	....
3370.789	787	788	789	−2	−1	−2
3399.337	339	338	337	+2	+1	+2
3445.155	152	154	154	−3	−2	−2
3485.344	343	346	345	−1	−3	−2
3515.820	822	821	821	+2	+1	+1
3556.879	878	883	881	−1	−5	−3
3606.681	682	....	682	+1	....	±0
3640.391	392	392	392	+1	±0	±0
76.312	312	....	313	±0	....	−1
Mean to 3300	....	....	....	+2.7	+1.0	−0.8
Mean after 3300	....	....	....	+0.1	−0.8	....

COMPARISON WITH FORMER MEASUREMENTS

Comparison with such I. Å. (Table 5) standards as occur in the region shows a mean difference of ±0.0015 Å and a systematic difference of half as much. The data are insufficient to establish the reality of so small a systematic difference. Table 5 also gives a comparison of my values with those of Buisson and Fabry[11] and of Pfund. Prof. Pfund kindly furnished me with a list of some of his lines which have not appeared in print. The systematic difference, Burns−Fabry and Buisson, is zero in the region of 3300 Å to 3676 Å. This difference in the region 2851 Å

[10] See Note 1, p. 181.

[11] See note 2, p. 181.

to 3300 Å is +0.0027, which is too large to be accidental. This systematic change at 3300 Å is supported to a large extent by the differences Burns – Pfund, yet it is difficult to see how anything systematic could enter into my measurements at this point, as all lines are measured on plates which covered the whole region at once.

Between 3513 Å and 3622 Å there are 21 lines common to the present table and the measurements of Miss Howell.[12] This investigator used two gratings. One of these was ruled by Rowland and the other by Anderson. Both of these were 6-inch gratings of 21 feet radius; the former was ruled 20 000 lines per inch, the latter 15 000. Miss Howell used a 4-mm arc fed by 110 volts and running at 5.5 to 6.5 amperes. The I. Å. standards 5266, 5371, 5405, and 5434 were measured in the second order, and the lines to be determined were measured in the third order. Three I. Å. standards occur in this list, and the mean difference Howell – I. Å. is +0.0023 Å. For the same lines, B. I. (Burns interference) – I. Å. = −0.0007, so H – B. I. = +0.0030 Å. Three lines are not enough to furnish a basis for any conclusions, but it is to be noted that the mean difference H – B. I. for 21 lines is +0.0027 Å, and for 9 lines B. I. – I. Å. = −0.0008 Å.

It seems, then, reasonably safe to assume that the mean of Miss Howell's measurements is about 0.002 Å above the I. Å. scale at this point. This may be due to a discrepancy between the green and violet I. Å. standards, which in turn may be due to the variation of the wave lengths of the iron lines with changed conditions of the source. Aside from the systematic difference the mean value of H – B. I. is ±0.0015, which is remarkably small. Both the systematic and accidental difference between the two series is slightly reduced by using only the values which were determined by the 20 000-line grating instead of the means of the results which Miss Howell measured by each grating.

There are two series of measurements made by means of gratings, which extend throughout the region under discussion, the one by Burns,[13] the other by Viefhaus.[14] The former used the second order of a 6-inch Rowland grating of 21 feet radius, which

[12] Howell, Astroph. J., 39, p. 230; 1914.

[13] Burns, Zs. f. wiss. Phot., 12, p. 207, 1913; and Lick Obs. Bulletin, 8, p. 27; 1913.

[14] Viefhaus, Zs. f. wiss. Phot., 13, pp. 209, 245; 1914.

was ruled 20 000 lines to the inch. He used the center of a long arc which was fed by a storage battery of 90 volts and burned at 6.5 amperes. Viefhaus used the center of a long arc, which was fed by 220 volts and burned at 7 amperes. His grating was by Rowland; it was ruled 10 000 lines to the inch and had over 45 000 lines. In the second order the scale was about 3 Å per millimeter. Comparing the present values with the grating measurements of Burns a mean difference of ±0.0028 Å is found. For the measurements of Viefhaus the mean difference is ±0.0056 Å.

Both series show the systematic difference due to the discrepancy in the region 2851 Å to 3300 Å between Buisson and Fabry values and those found in this article. In the region where I, Å. standards exist there is no systematic difference in V. – B. I. and B – B. I., which is large enough to reduce the residuals materially. In both series the need of more numerous standards is quite apparent, for large differences of like sign persist in some cases for 100 Å or more. As an extreme case of these departures consider the values of Burns between 3225 Å and 3323 Å. The standards in this region did not agree on his plates and as 3271 was broad and hazy it was not used, the reduction curve being passed through the other standards. This proves to have been a mistake, as shown by the residuals B – B. I. From 3225 to 3323 the residuals are: –2, +4, +5, +4, +9, +7, +5, +5, +7, +8, +4, +4, +3, +3, +1, +3, –1, ±0, ±0. The presence of two or three more standards between 3240 Å and 3300 Å would undoubtedly have made this large error impossible.

Goos [15] has recently published a series of wave-length determinations which extends from 3370 Å to the end of my list, the two series having 58 lines in common. This investigator used the standard conditions of the arc, which were recommended by the international wave-length committee. These conditions are for this region: Arc 6 mm long, of which only the central 2 mm are to be used; 4 amperes; 220 volts; 7 mm rods of iron; arc vertical, with positive pole above. The grating was used in parallel light, giving a dispersion in the second order of 2.5 Å per millimeter. This grating was ruled by Anderson and had some 78 000 lines.

[15] Goos, Astron. Nach., 199, p. 31; 1914.

The mean difference with regard to sign between the measurements by Goos and Burns's interference values is −0.0001 Å; in other words, the systematic difference is nil.

The tendency for residuals to be either positive or negative over a large interval of wave length is not so pronounced as in the case of the other grating results, which have been cited. The mean difference Goos −B. I. without regard to sign is ±0.0019 Å. This excellent agreement leads one to suppose that both series are nearly free from systematic error, and that the accidental errors seldom exceed one part in a million. No doubt the lines which show large residuals will not prove to be satisfactory as standards, but there is not sufficient homogeneous material at hand to warrant the discussion of this matter at present. A study of the lines by means of etalons of different thickness will eventually be undertaken. Considering only the lines which have been measured by interference, each series of grating measurements agrees slightly better with the interference values than with any other grating series.

While for the greater part of the region 2987 Å to 3701 Å satisfactory lines have been found at intervals of 10 Å or less, yet there are a few gaps of 15 to 20 Å where suitable lines are lacking. Both faint and strong lines were measured where that was possible. The advantage of having standards differing greatly in intensity has been discussed in previous papers.[16] The investigation will be extended as soon as possible to shorter and longer wave lengths.

SUMMARY

Between the limits 2851 Å and 3701 Å, 131 wave lengths have been measured in conformity with the recommendations of the international wave-length committee. Where it was found possible, faint lines as well as strong ones were measured. Throughout the greater part of the regions, 2987 Å to 3701 Å lines were measured at intervals of 10 Å or less.

The spectroscope used was a 21-foot grating, mounted in parallel light, and the etalon was 3.75 mm thick. The method was that of Buisson and Fabry.

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[16] Burns, Zs. f. wiss. Phot., 12, p. 207, 1913; and 13, p. 235, 1915.

The mean difference between the present observations and the I. Å. standards is one part in two million; the systematic difference is half of that. Between 2851 Å and 3300 Å, where there are no I. Å. standards, a comparison with the work of Buisson and Fabry shows a systematic difference of one part in a million; allowing for the systematic difference, there is a mean difference of one part in three million. The systematic difference Burns – Pfund is +0.001 Å.; the mean difference is ±0.0018 Å in the region of wave length shorter than 3300.

Comparisons with different series of grating measurements confirms the belief, which is gaining ground, that secondary standards are needed at much closer intervals than was at first supposed.

WASHINGTON, February 26, 1915.

NOTES ON COMPARISONS OF LENGTHS OF LIGHT WAVES BY INTERFERENCE METHODS, AND SOME WAVE LENGTHS IN THE SPECTRUM OF NEON GAS

By W. F. Meggers

INTRODUCTION

The determination of secondary light-wave length standards in the arc spectrum of iron from $\lambda = 2900$ Å to $\lambda = 3700$ Å was recently completed at this Bureau, the results of which are published in the preceding article. To obtain these, it was necessary to redetermine the corrections due to change of phase at reflection from the nickeled-quartz interferometer plates. Messrs. Fabry and Buisson used these identical plates in similar work eight years ago [17] and found the corrections for change of phase at reflection to be an inverse linear function of the wave length.[18] Their method of obtaining this correction was again applied to these films recently, but an iron arc served as a source of light instead of a mercury lamp. The results confirmed the linear nature of the phase change.

Then the phase-change correction was found by another method, which will be described here. For this new determination neon in a fused-quartz vacuum tube was used as a source of light, and some experiences in this connection may be of interest and value to those engaged in this kind of work. Some wave lengths of neon lines, a new type of neon lamp, and a simple way of finding the order of interference in an etalon are incidental results of this phase-change determination, and notes on these points are contained in this article.

[17] Journal de Physique, 7, p. 169; 1908.

[18] Journal de Physique, 7, p. 417; 1908.

DETERMINATION OF THE PHASE-CHANGE CORRECTION

At reflection from metallic films light apparently penetrates the films a short distance, and the amount of this penetration varies with the wave length. This phenomenon is considered as a change of phase at the reflecting surface.

The correction due to change of phase at reflection which must be applied to wave lengths obtained by interference methods is usually made for each wave length either as a correction to the thickness of the etalon[19] e or to the order of interference[20] p. The purpose of this paragraph is to show how the correction can be made directly to the wave lengths from their uncorrected values as determined from a thin etalon e_1 and a thick etalon e_2. This method was used by Dr. Burns in his interference measurements of wave lengths in the spectrum of the iron arc $\lambda = 8824$ to $\lambda = 5434$.[21] The values from e_1 will be smaller or larger than those from e_2, depending on their position in the spectrum and on the nature of the metallic film. Let a point λ' in the spectrum be chosen as a standard of wave length and represent the measurements of another wave length λ as obtained from e_1 and e_2 by λ_{e_1} and λ_{e_2}, respectively. Let the difference $\lambda_{e_2} - \lambda_{e_1} = c$. If the effect of phase change be regarded zero at λ', the total correction to λ can be shown to be proportional to c.

Let $\delta\lambda_{e_1}$ and $\delta\lambda_{e_2}$ represent the phase-change error in wave length from e_1 and e_2, respectively. If the penetration of light into the films at reflection be regarded as an increase ϵ in the optical distance e between the interferometer plates, then

$$\lambda = \lambda_{e_1} + \delta\lambda_{e1} = \frac{2\,(e_1 + \epsilon)}{p_1} = \frac{2\,e_1}{p_1} + \frac{2\,\epsilon}{p_1}$$

and

$$\lambda = \lambda_{e_2} + \delta\lambda_{e_2} = \frac{2\,(e_2 + \epsilon)}{p_2} = \frac{2\,e_2}{p_2} + \frac{2\,\epsilon}{p_2}$$

But $\lambda_{e_1} = \frac{2\,e_1}{p_1}$ and $\lambda_{e_2} = \frac{2\,e_2}{p_2}$ since the measured values of λ are

[19] Journal de Physique, 7, p. 169; 1908.
[20] Astro-Physical Journal, 28, p. 197; 1908.
[21] Journal de Physique, (5) 3, p. 457; 1913.

always expressed in terms of the etalon thicknesses which result from the standard wave length λ' and the orders of interference which are obtained from measurements on the rings. Consequently,.

$$\delta\lambda_{e_1} = \frac{2\,\epsilon}{p_1} \text{ and } \delta\lambda_{e_2} = \frac{2\,\varepsilon}{p_2}$$

Then $\delta\lambda_{e_1}/\delta\lambda_{e_2} = p_2/p_1$, and since p is directly proportional to e for a given value of λ we have

$$\delta\lambda_{e_1}/\delta\lambda_{e_2} = e_2/e_1 \text{ or } \delta\lambda_{e_1} - \frac{e_2}{e_1}\delta\lambda_{e_2} = o \tag{1}$$

Also

$$\delta\lambda_{e_1} - \delta\lambda_{e_2} = \lambda_{e_2} - \lambda_{e_1} = c \tag{2}$$

Subtracting (2) from (1) gives

$$\delta\lambda_{e_2}\left(\frac{e_2}{e_1} - 1\right) = c \text{ or } \delta\lambda_{e_2} = \frac{e_1\, c}{e_2 - e_1} \tag{3}$$

The phase-change correction from λ' to λ for any other thickness e is then

$$\frac{e_2}{e}\,\delta\lambda_{e_2} \text{ or } \frac{e_2}{e} \cdot \frac{e_1\, c}{e_2 - e_1}$$

In this way this error can be corrected from point to point in the spectrum.

For example, several wave lengths in the ultra-violet portion of the spectrum of neon were measured with 2-mm and 15-mm etalons, using $\lambda' = 5852.4862$ Å as a standard.

λ_{e_1}	λ_{e_2}	$\lambda_{e_2} - \lambda_{e_1} = c$
3417.888	3417.903	+.015 Å
3447.685	3447.703	.018
3520.457	3520.472	.015

The mean correction to λ in this region is therefore proportional to 0.016 Å and the amount which must be added to λ_{e_2} is

$$\delta\lambda_{e2} = \frac{e_1\, c}{e_2 - e_1} = \frac{2 \times 0.016}{15 - 2} = 0.0025 \text{ Å}$$

Thus, the mean of three measures of $\lambda = 3417+$ with 15 mm etalons gave $\lambda_{e2} = 3417.9031$, whence the true wave length is

3417.906 Å to three decimal places. Similarly, several lines near $\lambda = 6500$ gave $\lambda_{e2} - \lambda_{e1} = c = -0.004$ from which $\delta\lambda_{e2} = \frac{2 \times -0.004}{15-2} = -0.0005$ Å. The mean of three measures of $\lambda = 6532+$ with 15 mm etalons gave $\lambda_{e2} = 6532.8834$ Å. The correct wave length is therefore 6532.883 Å.

The method used by Fabry and Buisson to determine the phase change correction consists in finding the difference in optical distances between the interferometer plates for different wave lengths. This can be done by finding the relatively small orders of interference p and p' for two wave lengths λ and λ' at the same point of an interferometer arranged with a thin wedge-shaped air space so as to give localized straight-line fringes. Then the difference in double optical thicknesses e and e' at this point for λ and λ' is $\epsilon = 2\ (e - e') = p\lambda - p'\ \lambda'$. From their curve ϵ between $\lambda = 6500$ and $\lambda = 3460$ was equal to 21 $\mu\mu$ or 210 Å. If the correction to wave length be regarded zero at $\lambda = 6500$ the correction to $\lambda' = 3460$ from a 15 mm etalon becomes $\frac{210 \times 3460}{30 \times 10^7} = 0.0024$ Å. The above measures on the neon lines give the correction over this interval as $0.0025 + 0.0005 = 0.0030$ Å. This difference may represent a real change in the film with time.

Whenever ϵ varies linearly with λ as in the case of these films, the correction to any wave length λ is $\frac{\delta\lambda_{e2}}{\lambda - \lambda'}$ angstrom for each angstrom, which separates λ from the standard wave length used in the measurement. Thus the mean of three measures of $\lambda = 7032.+$ gave $\lambda_{e2} = 7032.4143$ Å. The correction is $\frac{0.0030}{6500 - 3460} \cdot (5852 - 7032) = -0.0012$ and the true wave length is 7031.413 Å.

The difference $\lambda_{e2} - \lambda_{e1} = c$, upon which the correction depends, is larger the greater e_2 is and the smaller e_1 is. The accuracy of its determination is thus increased as the order of interference in e_2 becomes larger. The use of a source of light which will give a high order of interference is therefore to be recommended. Since it is always advisable to use as large as possible an etalon in interferometer measures of wave length, sufficient data is immediately

at hand from which to make the phase change correction to the wave lengths measured if an additional set of measures is made with a thinner etalon.

WAVE LENGTHS IN THE SPECTRUM OF NEON

For measurements of wave lengths in the spectrum of neon the wave length of the neon yellow line $\lambda = 5852.4862$ Å, measured by Priest,[21] in terms of the cadmium red line $\lambda = 6438.4696$ was used as a standard. Eight wave lengths $\lambda = 5852$ to $\lambda = 6304$, which Priest measured, were again compared with this standard and found to agree very satisfactorily. The largest deviations were ± 0.002 Å except for $\lambda = 6304.789$, where Priest's value is 0.004 Å larger. In addition, 7 longer wave lengths and 10 in the ultra-violet were measured and are here presented:

3369.903 c	6506.532 b
3417.906 a	6532.883 a
3447.706 a	6598.951 a
3454.158 a	6678.274 a
3460.533 c	6717.042 a
3466.547 a	6929.468 a
3472.573 a	7032.413 a
3501.220 c	
3515.196 c	
3520.474 a	

The letters a, b, and c indicate probable relative accuracy in the determinations. The values marked "a" were obtained with the 15-mm etalon and should be quite reliable, while those marked "b" and "c" come from 7.5 mm and 2 mm etalons, respectively, and probably contain larger errors. These wave lengths are only provisional and will be verified by a direct comparison with the cadmium red standard as soon as possible.

Attention is called to the neon tubes which were used in this work. Their design is shown in Fig. 2. They are made of fused quartz and contain flat circular aluminum electrodes sealed into the ends. We take this occasion to thank the Cooper-Hewitt Electric Co., of Hoboken, for the interest and kindness shown in making these excellent tubes for us. They are extremely efficient

[21] This Bulletin, 8, p. 539; 1911–12.

and can be made to emit light of great intensity without appreciable heating or electrical evaporation of the electrodes. One of these tubes has seen over 25 hours' service at high intensity and shows no signs of electrode disintegration or gas occlusion. The tubes were filled at the Bureau of Standards with gas which was obtained from M. Claude. They were thoroughly exhausted, then filled with neon and a discharge passed through for several hours while they were alternately exhausted and filled three or four times. The electrodes probably became saturated with the gas in this way. The tubes were finally sealed off at a gaseous pressure corresponding to about 1 mm dark space.

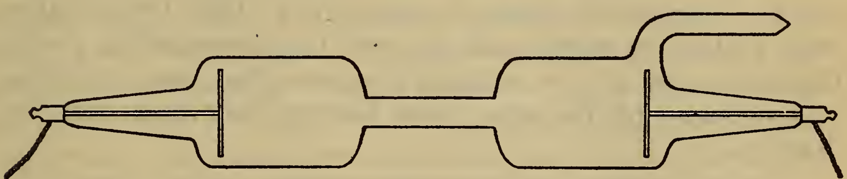

FIG. 2.—*Scale: Half size.*

DETERMINATION OF THE ORDER OF INTERFERENCE

The thickness of the layer of air between two interferometer plates is $e = \frac{\lambda p}{2} = \frac{\lambda}{2} (P + p')$ where p is the order of interference at the center of the system of circular fringes. P is an ordinal number representing the waves in the path difference producing any ring, and p' is the fractional portion calculated from observations on the rings with the aid of $p' = P\theta^2 d^2/8r^2$. The linear diameters of the ring and gauge images are represented by d and r, respectively, and θ is the angle at the lens subtended by the gauge. A roughly approximate value of P is sufficient for the first calculation of p'. If P is the order of the first ring from the center, p' will lie between 0 and 1.

To get the exact value of P quickly and easily the following modification of the methods used by Messrs. Perot and Fabry [22] and by Lord Rayleigh [23] is suggested. The use of 4 or 5 wave lengths from the spectrum of neon is recommended because of

[22] Annales de Chimie et de Physique, (7) 17, p. 289; 1899. [23] Phil. Mag., 11, p. 685; 1906.

their particular applicability: Find the ratios R of any wave length to each of the others, e. g., $\frac{5852.4862}{\lambda}$. This, of course, gives the rate at which the order for each λ changes when that for $\lambda = 5852.4862$ changes one wave length. These values of λ and R can subsequently be used with any etalon. The following example will illustrate their use. This particular etalon is assumed to possess the length it was ordered to have, i. e., 15 mm. The approximate order of interference, P_{5852}, assuming the double thickness 30 mm is then $\frac{30}{0.0005852486} = 51260$. The fractional order p', however, is found to be 0.777, so that the tentative order p_λ may be called 51260.777 and the corresponding double thickness $51260.777 \times 0.0005852486 = 30.0002990$ mm. Dividing this thickness by the other wave lengths gives their tentative orders p_λ.

λ	$R=\frac{5852.4862}{\lambda}$	$p'=P\frac{\theta^2 d^2}{8r^2}$	$p_\lambda=\frac{30.0002990}{\lambda(\text{in mm})}$	$p=\frac{29.9891793}{\lambda\ (\text{in mm})}$
3417.903	1.7123	0.482	87773.992	87741.458
5852.4862	1.0000	.777	51260.777	51241.777
5881.894	.9950	.578	51004.487	50985.582
6096.161	.9600	.554	49211.789	49193.549
6304.789	.9283	.715	47583.351	47565.714

The fractional order for $\lambda = 5881$ computed on this basis is $(0.578 - 0.487 =)$ 0.091 smaller than p' calculated from observations on the rings. Since $R = 0.9950$ coincidence should occur if P_{5852} is reduced by $\frac{0.091}{1.0000 - 0.9950} = 18$. This gives the order of magnitude of the change necessary in P_{5852} to get the true whole number.[24] This required change can be obtained more accurately from the other wave lengths. Thus,

$$\lambda = 6096 \text{ gives } \frac{1.554 \quad - 0.789}{1.0000 - 0.9600} = \frac{0.765}{0.040} = 19.12$$

Similarly, $\lambda = 6304$ gives 19.02 and $\lambda = 3417$ gives 18.94. This shows that P_{5852} is 19 too large and must be reduced from

[24] The next coincidence would require a change of just 200 waves either above or below this one and such a large change is excluded by the preliminary knowledge of the approximate length of the etalon.

51260.777 to 51241.777 which gives the true thickness $2e=51241.777 \times 0.0005852486 = 29.9891793$ mm. The correctness of this can be tested very readily by simply subtracting proportional amounts from the provisional p_λ previously found for the other wave lengths and observing how well the resulting fraction agrees with the p' calculated from the rings. For example, p for $\lambda = 6096$ is equal to $49211.789-(0.9600 \times 19) = 49193.549$, while the observed p' was 554. The remaining differences are very small considering that experimental errors and the change of phase at reflection are present. After the correction for phase change at reflection from these plates is once determined it can be applied to the wave lengths used, so that the resulting agreement between fraction orders is even more perfect. This procedure is not necessary but it is advisable in the case of larger etalons. The particular advantage which lies in the spacing of the neon lines used in this method is apparent. They enable one to find the exact length of an etalon quickly and without difficulty when only a roughly approximate value is known. In the above example 15 mm was used because this was the length ordered and we had faith in its approximate correctness. A Brown & Sharpe micrometer caliper may be used to give a sufficiently accurate value with which to begin on any etalon.

SUMMARY

A convenient way to apply the corrections which are necessary to interference measurements of wave lengths because of the change of phase at reflection is described. The error can be corrected for each wave length directly from its measured values obtained from thick and thin etalons. The determination of this correction is illustrated by some measurements of wave lengths in the spectrum of neon. The values of ten lines from $\lambda = 3369$ to $\lambda = 3520$ and seven from $\lambda = 6506$ to $\lambda = 7032$ are given. An example is given to show how the determination of the exact order of interference, or the optical measurement of length can be made easily and rapidly with the aid of certain wave lengths of neon radiation.

WASHINGTON, February 26, 1915.